

Energy-dependence of skin-mode fraction in $E1$ excitations of neutron-rich nuclei

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Abstract. We have extensively investigated characters of the low-energy $E1$ strengths in $N > Z$ nuclei, by analyzing the transition densities obtained by the HF+RPA calculations with several effective interactions. Crossover behavior has been confirmed, from the skin mode at low energy to the pn mode at higher energy. Decomposing the $E1$ strengths into the skin-mode, pn -mode and interference fractions, we show that the ratio of the skin-mode strength to the full strength may be regarded as a generic function of the excitation energy, insensitive to nuclides and effective interactions, particularly beyond N .

1 Introduction

By recent experiments, sizable $E1$ strengths have been observed at low excitation energy in a number of $N > Z$ nuclei, and are called pygmy dipole resonance (PDR) [1]. Low-energy $E1$ strengths have been predicted in many $N > Z$ nuclei by a systematic calculation as well [2]. However, their character has not yet been established. Although oscillation of the neutron skin against the core (skin mode) has been argued in connection to the PDR, there remain other possibilities, *e.g.* fragmentation of the proton-neutron oscillation (pn mode) whose dominant part forms the giant dipole resonance (GDR). As low-energy $E1$ strengths may greatly influence (n, γ) reaction rates under astrophysical environment, it is significant to comprehend their character including their energy- and nucleus-dependence. Moreover, the skin-mode strengths could be correlated to the slope parameter of the nuclear symmetry energy L , which attracts interest in relevance to structure of neutron stars.

To investigate characters of the low-energy $E1$ excitations, we have analyzed transition densities obtained from the HF+RPA calculations in the doubly-magic nuclei [3]. By decomposing the transition matrix elements into the skin-mode and pn -mode fractions via the transition densities, energy-dependence of the skin-mode fraction has been argued. Here we extensively study energy-dependence of the skin-mode fraction.

2 Decomposition of $E1$ strengths

We have proposed a decomposition method of the low-energy $E1$ transition matrix elements into the pn mode and the skin mode via the transition densities, so that their mixing could be handled in a straightforward manner. With the

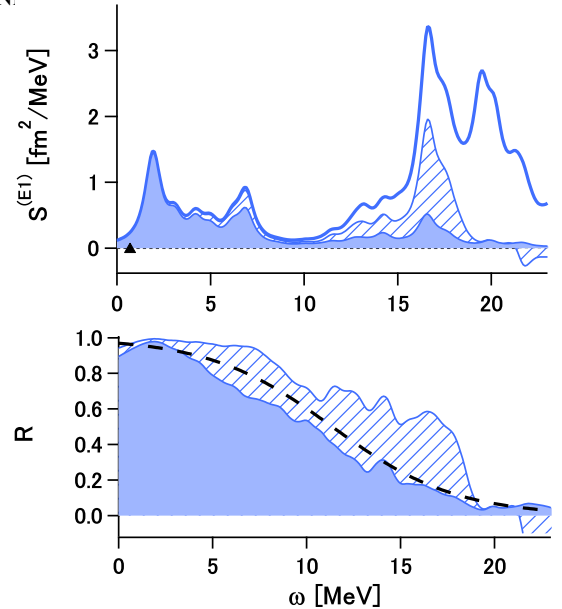


Figure 1. $E1$ strength function $S_{\text{mode}}^{(E1)}(\omega)$ (upper panel) and ratio $R_{\text{mode}}(\omega)$ in ^{86}Ni , by the HF+RPA calculation with DIS. Blue-shaded and hatched areas present the skin mode and the interference contributions, respectively. Blue thick solid line in the upper panel gives the full $E1$ strength $S^{(E1)}(\omega)$. Black triangle attached to the horizontal axis indicates the neutron threshold in the HF calculation. Dashed line in the lower panel is $R_{\text{skin}}(\omega)$ of Eq. (5) with the fitted ω_{cr} and D_{cr} .

proton and neutron transition densities of the excitation to the 1^- state $|\alpha\rangle$,

$$\delta\rho_{\tau_z}^{(\lambda=1)}(r; \alpha) = \langle \alpha | \sum_{i \in \tau_z} \delta(\mathbf{r} - \mathbf{r}_i) r_i Y^{(1)}(\hat{\mathbf{r}}_i) | 0 \rangle \quad (\tau_z = p, n), \quad (1)$$

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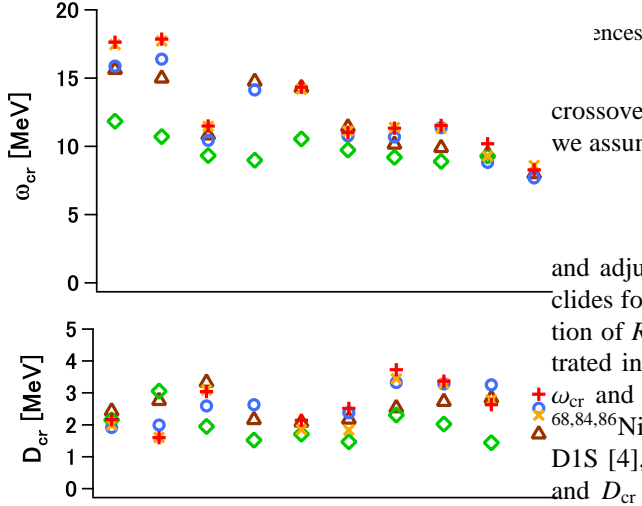


Figure 2. Fitted values of ω_{cr} and D_{cr} , for $^{22,24}\text{O}$, $^{52,60,70}\text{Ca}$, $^{68,84,86}\text{Ni}$, ^{132}Sn and ^{208}Pb from left to right. Each symbol represents the effective interaction used in the HF+RPA calculation; SkI2 (green diamonds), D1S (blue circles), D1M (brown triangles), M3Y-P6 (orange crosses) and M3Y-P7 (red pluses).

the $E1$ transition density is given by

$$\delta\rho^{(E1)}(r; \alpha) = \frac{N}{A}\delta\rho_p^{(\lambda=1)}(r; \alpha) - \frac{Z}{A}\delta\rho_n^{(\lambda=1)}(r; \alpha). \quad (2)$$

Depending on the position, the $E1$ transition density is classified into $\delta\rho_{pn}^{(E1)}$ and $\delta\rho_{skin}^{(E1)}$; if $\delta\rho_p^{(\lambda=1)}/\delta\rho_n^{(\lambda=1)} > -\lambda_s$ with $0 < \lambda_s \ll 1$, we take

$$\delta\rho_{pn}^{(E1)}(r; \alpha) = 0, \quad \delta\rho_{skin}^{(E1)}(r; \alpha) = \delta\rho^{(E1)}(r; \alpha), \quad (3)$$

and otherwise,

$$\delta\rho_{pn}^{(E1)}(r; \alpha) = \delta\rho^{(E1)}(r; \alpha), \quad \delta\rho_{skin}^{(E1)}(r; \alpha) = 0. \quad (4)$$

We adopt $\lambda_s = 0.05$ below. The pn -mode and skin-mode matrix elements can be obtained by integrating the transition densities. The $E1$ strength is then decomposed into the pn -mode, skin-mode and interference contributions for individual α . The corresponding strength function is denoted by $S_{\text{mode}}^{(E1)}(\omega)$ ('mode' = ' pn ', 'skin' or 'intf'). The ratio of $S_{\text{mode}}^{(E1)}$ to the full strength $S^{(E1)} = \sum_{\text{mode}} S_{\text{mode}}^{(E1)}$ at the excitation energy ω is denoted by $R_{\text{mode}}(\omega)$.

3 Energy-dependence of skin-mode fraction

Figure 1 displays $S_{\text{mode}}^{(E1)}(\omega)$ and $R_{\text{mode}}(\omega)$ in ^{86}Ni , obtained by the HF+RPA calculation with the D1S interaction [4]. Crossover behavior of the $E1$ excitations has been found, from the skin mode at low energy to the pn mode at higher energy. By calculations in a number of spherical $N > Z$ nuclei with several effective interactions, the ratio of the skin-mode strength to the full strength R_{skin} turns out to have generic energy-dependence, insensitive to nuclide and to effective interactions in the energy region of the

crossover

[3]. In order to view this feature more clearly, we assume a model for $R_{\text{skin}}(\omega)$,

$$R_{\text{skin}}(\omega) = \left[1 + \exp((\omega - \omega_{cr})/D_{cr})\right]^{-1}, \quad (5)$$

and adjust the parameters ω_{cr} and D_{cr} in individual nuclides for individual interactions so as to minimize deviation of $R_{\text{skin}} \cdot S^{(E1)}$ from $S_{\text{skin}}^{(E1)}$. Degree of fitting is illustrated in the lower panel of Fig. 1. The fitted values of ω_{cr} and D_{cr} are depicted in Fig. 2, for $^{22,24}\text{O}$, $^{52,60,70}\text{Ca}$, $^{68,84,86}\text{Ni}$, ^{132}Sn and ^{208}Pb with the interactions SkI2 [5], D1S [4], D1M [6], M3Y-P6 and M3Y-P7 [7]. Then ω_{cr} and D_{cr} represent how $R_{\text{skin}}(\omega)$ varies according to nuclides and effective interactions.

It is confirmed, as pointed out in Ref. [3], that $R_{\text{skin}}(\omega)$ is insensitive to nuclides and effective interactions. In particular, the extracted values of ω_{cr} is quite stable from ^{68}Ni to ^{208}Pb , surprisingly insensitive to the effective interactions, although there is certain fluctuation in O and Ca. Fluctuation of the extracted values of D_{cr} is not significantly large. This generic nature of the skin-mode ratio may be helpful in extracting skin-mode strengths from measurements.

4 Summary

We have extensively investigated characters of the low-energy $E1$ strengths in $N > Z$ nuclei by the HF+RPA calculations. Confirming the crossover behavior from the skin mode at low energy to the pn mode at higher energy, we apply a method decomposing the $E1$ strengths into the skin-mode, pn -mode and interference fractions, via the transition densities. In Ref. [3] the ratio of the skin-mode strength to the full strength was suggested to be a generic function of the excitation energy, insensitive to nuclides and effective interactions. By fitting parameters of a model function for the ratio, this insensitivity is further clarified, particularly beyond Ni.

This work is financially supported as Grant-in-Aid for Scientific Research No. 24105008 by MEXT, and No. 25400245 by JSPS.

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